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SILICON-SAPPHIRE WAVEGUIDES(U) NAVAL OCEAN SYSTEMS  
CENTER SAN DIEGO CA D J ALBARES ET AL. NOV 87

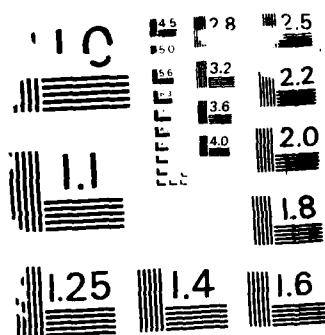
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<p>The first silicon-on-sapphire optical waveguides have been demonstrated. Waveguiding at <math>\lambda=1.3</math> microns has been observed in silicon films 0.95 and 1.5 microns thick and in raised strip structures 1.5 microns thick.</p> <p>Previously, an epitaxial silicon-on-silicon technique was used to construct silicon waveguides for <math>\lambda=1.3</math> or 1.55 microns, but the Si-on-Si technique allows guided light to spread evanescently into the lossy substrate because the refractive index step between substrate and guiding layer is approximately 0.01. However, tighter mode confinement is offered at these wavelengths by silicon-on-insulator (SOI) structures. This occurs because the Si-to-dielectric compositional change gives a larger index-step than the Si-to-Si doping profile change. Various SOI waveguide structures are possible including silicon-on-SiO<sub>2</sub>, MBE-silicon-on-CAF and silicon-on-sapphire (SOS). SOS is an attractive candidate structure because of sapphire's excellent mechanical, electrical and optical properties and of its development for the electronics industry. Electronic device fabrication on the same chip with the optical waveguide devices (optoelectronic integration) is possible.</p> <p>Waveguide theory predicts a single TE guided mode of 1.3 micron radiation in an SOS film below 0.22 microns in thickness. The ordinary refractive index of the sapphire substrate is 1.75 and the Si index is 3.50. We obtained SOS films of 0.3, 0.95 and 1.5 microns thickness and for these, theory predicts 2, 5, and 7 TE modes respectively. Evanescent field penetration depths into the sapphire is on the order of 0.1 microns according to calculations.</p>													
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We report finding optical waveguiding on 0.95 and 1.5 micron-thick SOS with both planar and raised strip structures in accord with the general features predicted. Thus far we have not observed waveguiding in the 0.3 micron SOS film, probably due to Si/Sapphire interface scattering losses and low launching efficiency. The propagation length in the various samples ranged from 3 to 5 mm. Waveguide input and output edges were prepared by cleaving a wafer into parallelopipeds. With a diamond-tip tool, a scribe mark was made on the Si side along or perpendicular to a Si (110) direction at  $+45^\circ$  or  $-45^\circ$  with respect to the projected C-axis of the substrate), and the wafer was snapped from pressure applied to the sapphire side. Two cleaves produced parallel flat facets on the Si film. The Si film resistivity was greater than 100 Ohm-cm.

Strip patterns were formed in a photoresist layer on the SOS wafers via standard photolithographic techniques. With the photoresist as an etch mask, the Si film was preferentially etched down to the sapphire with a KOH solution, yielding Si strips 3 to 30 microns wide. As before, the ends of the Si strips were cleaved. The 3-dimensional guide is illustrated in Figure 1, and Figure 2 shows a SEM photograph of the 1.5-micron-thick strip waveguide structure. Other techniques such as ion milling and plasma etching are expected to produce improved waveguide sides, thereby reducing scattering losses. Furthermore it is possible to stop the silicon removal before reaching the sapphire, thereby leaving a rib waveguide structure.

Light from a 1.3-micron laser diode was focussed with a 43X lens into the entrance end of the films and the near-field radiation pattern of the exit end was imaged onto an infrared vidicon. Waveguiding was observed in the Si films of 0.95 and 1.5 microns thickness as expected from theory. For the Si strips 30 microns wide, we observed two or three output spots, depending upon the launching conditions. Single output spots were observed, with the strips of 8 and 4 microns width.

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## SILICON-ON-SAPPHIRE WAVEGUIDES

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### Abstract

The first silicon-on-sapphire optical waveguides have been demonstrated. Waveguiding at  $\lambda=1.3$  microns has been observed in silicon films 0.95 and 1.5 microns thick and in raised strip structures 1.5 microns thick.

Previously, an epitaxial silicon-on-silicon technique was used to construct silicon waveguides for  $\lambda=1.3$  or 1.55 microns<sup>1</sup>, but the Si-on-Si technique allows guided light to spread evanescently into the lossy substrate because the refractive index step between substrate and guiding layer is approximately 0.01. However, tighter mode confinement is offered at these wavelengths by silicon-on-insulator (SOI) structures. This occurs because the Si-to-dielectric compositional change gives a larger index-step than the Si-to-Si doping profile change. Various SOI waveguide structures are possible<sup>2</sup> including silicon-on-SiO<sub>2</sub>, MBE-silicon-on-CAF<sub>2</sub>, and silicon-on-sapphire (SOS). SOS is an attractive candidate structure because of sapphire's excellent mechanical, electrical and optical properties and of its development for the electronics industry. Electronic device fabrication on the same chip with the optical waveguide devices (optoelectronic integration) is possible.

Waveguide theory<sup>3</sup> predicts a single TE guided mode of 1.3-micron radiation in an SOS film below 0.22 microns in thickness. The ordinary refractive index of the sapphire substrate is 1.75 and the Si index is 3.50. We obtained SOS films of 0.3, 0.95 and 1.5 microns thickness and for these, theory predicts 2, 5 and 7 TE modes respectively. Evanescent field penetration depths into the sapphire is on the order of 0.1 microns according to calculations.

We report finding optical waveguiding in 0.95 and 1.5 micron-thick SOS with both planar and raised strip structures in accord with the general features predicted. Thus far we have not observed waveguiding in the 0.3 micron SOS film, probably due to Si/Sapphire interface scattering losses and low launching efficiency. The propagation length in the various samples ranged from 3 to 5 mm. Waveguide input and output edges were prepared by cleaving a wafer into parallelepipeds. With a diamond-tip tool, a scribe mark was made on the Si side along or perpendicular to a Si (110) direction at +45° or -45° with respect to the projected C-axis of the substrate), and the wafer was snapped from pressure applied to the sapphire side. Two cleaves produced parallel flat facets on the Si film. The Si film resistivity was greater than 100 Ohm-cm.

Strip patterns were formed in a photoresist layer on the SOS wafers via standard photolithographic techniques. With the photoresist as an etch mask, the Si film was preferentially etched down to the sapphire with a KOH solution, yielding Si strips 3 to 40 microns wide. As before, the ends of the Si strips were cleaved. The 3-dimensional guide is illustrated in Figure 1, and Figure 2 shows a SEM photograph of the 1.5-micron-thick strip waveguide structure. Other techniques such as ion milling and plasma etching are expected to produce improved waveguide sides, thereby reducing scattering losses. Furthermore it is possible to stop the silicon removal before reaching the sapphire, thereby leaving a rib waveguide structure.

Light from a 1.3-micron laser diode was focussed with a 43X lens into the entrance end of the films and the near-field radiation pattern at the exit end was imaged onto a photoreduced vidicon. Waveguiding was observed in the Si films 0.95 and 1.5 microns thick, as expected from theory. For the Si strips 30 microns wide, we observed two or three output spots, depending upon the launching conditions. Single output spots were observed, with the strips of 8 and 4 microns width.

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2. J. P. Lorenzo and R. A. Soref, unpublished memo, 1985.
3. D. Marcuse, *Theory of Dielectric Waveguides*, Academic Press, New York, 1974.

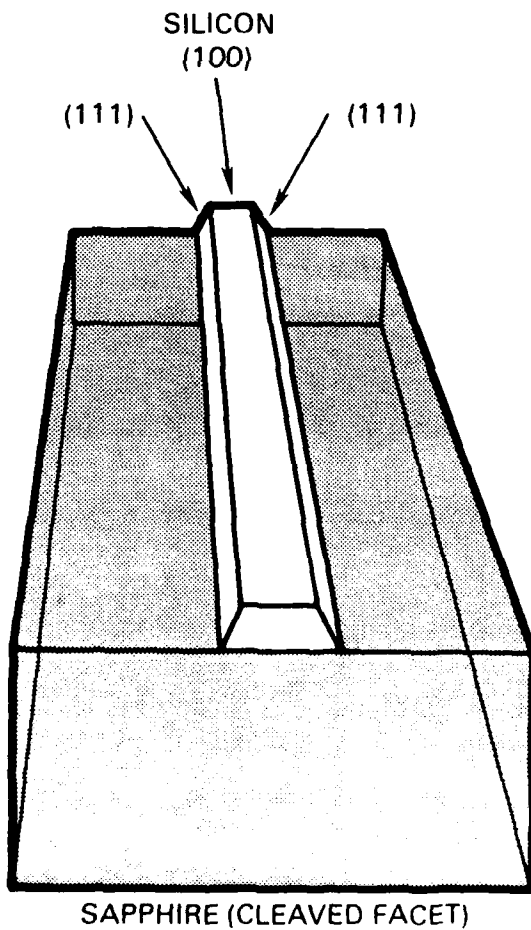


Figure 1. Perspective view of SOS raised strip waveguide illustrating crystal planes.

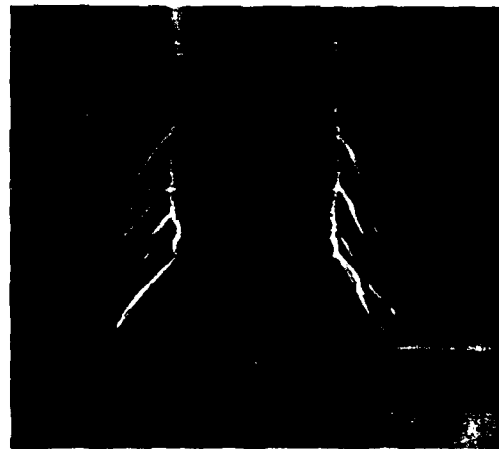


Figure 2. SEM photograph of SOS raised strip waveguide with chemically etched side walls. Magnification 20000X.

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